



Eco-Friendly Corrosion Inhibition of Mild Steel Pipelines Using Non-Edible Plant Extracts

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ABSTRACT

This study evaluates the potential of non-edible plant extracts as eco-friendly corrosion inhibitors for mild steel pipelines in acidic environments. Extracts obtained from *Cassia occidentalis*, *Lantana camara*, and *Ricinus communis* were investigated in a 2 M hydrochloric acid medium. Elemental analysis confirmed iron as the dominant constituent of the mild steel, while phytochemical screening revealed the presence of alkaloids, tannins, flavonoids, and saponins that promote protective surface adsorption. Corrosion rates and inhibition efficiencies were determined using the gravimetric weight loss method across varying exposure times. The results showed that inhibition efficiency increased with inhibitor presence but varied with exposure time, indicating an adsorption-controlled inhibition process. Among the extracts studied, *Cassia occidentalis* exhibited the highest inhibition efficiency, followed by *Lantana camara* and *Ricinus communis*. These findings demonstrate that non-edible plant extracts offer an effective, low-cost, and environmentally sustainable alternative to conventional synthetic corrosion inhibitors for industrial applications.

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1. INTRODUCTION

Corrosion of metallic materials poses a significant challenge to global infrastructure, resulting in substantial economic losses, safety risks, and environmental consequences. Recent studies have shown that corrosion-related degradation imposes a major financial burden on industries worldwide, particularly in sectors such as oil and gas, transportation, and manufacturing [1]. In addition to economic losses, corrosion of steel structures contributes to increased carbon emissions due to frequent repair, replacement, and the energy-intensive production of new materials [2]. Mild steel is widely used in these applications because of its low cost, availability, and favorable mechanical properties; however, it is highly susceptible to corrosion in acidic environments commonly encountered during industrial operations such as acid pickling, pipeline cleaning, and oil well acidizing.

The use of corrosion inhibitors is one of the most effective and practical approaches for mitigating corrosion in acidic media. Conventional corrosion inhibitors, which are often synthetic organic or inorganic compounds, function by adsorbing onto metal surfaces and forming protective films that reduce metal dissolution [3]. Despite their effectiveness, many synthetic inhibitors are associated with toxicity, high cost, and adverse environmental impacts, which limit their large-scale and long-term application [3], [14]. Consequently, the development of environmentally benign corrosion inhibitors has become an important research focus.

In recent years, plant extracts have emerged as promising green corrosion inhibitors owing to their biodegradability, availability, and rich chemical composition [4], [5]. These extracts contain various phytochemical constituents such as alkaloids, flavonoids, tannins, saponins, and other organic compounds with heteroatoms and π -electron systems that enhance their ability to interact with metal surfaces and inhibit

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corrosion reactions in acidic environments [4], [10]. Numerous studies have demonstrated the effectiveness of plant-based inhibitors for mild steel corrosion control in hydrochloric acid media, including extracts derived from *Azadirachta indica*, *Lawsonia inermis*, *Moringa oleifera*, and *Vernonia amygdalina* [6]–[9].

Adsorption of phytochemical constituents onto the metal surface is generally regarded as the primary mechanism responsible for corrosion inhibition by plant extracts [10]. Advanced investigations involving thermodynamic, kinetic, and surface analysis techniques have further confirmed the adsorption-controlled nature of many green corrosion inhibitors [11]–[13]. Nevertheless, gravimetric weight loss measurements remain a reliable and widely accepted method for evaluating long-term corrosion behavior and inhibitor performance, particularly under practical exposure conditions [10], [14].

Despite the growing body of literature on plant-derived corrosion inhibitors, many reported studies focus on edible plant materials, which raises concerns regarding competition with food resources and sustainability [5]. In addition, comparative studies involving multiple non-edible plant species under identical experimental conditions remain relatively limited, especially with respect to time-dependent corrosion behavior in strongly acidic media.

In this study, the corrosion inhibition performance of non-edible plant extracts derived from *Cassia occidentalis*, *Lantana camara*, and *Ricinus communis* was investigated for mild steel in a 2 M hydrochloric acid medium using the gravimetric weight loss method. The effect of exposure time on weight loss, corrosion rate, and inhibition efficiency was evaluated. Furthermore, qualitative phytochemical analysis was carried out to identify adsorption-active constituents responsible for corrosion inhibition. The findings of this work aim to contribute to sustainable corrosion mitigation strategies and to provide comparative insight into the effectiveness of selected non-edible plant extracts as eco-friendly corrosion inhibitors for mild steel in acidic environments

2. MATERIALS AND METHODS

2.1 Materials

Mild steel specimens were used as the test material for the corrosion inhibition study. Mild steel is widely employed in industrial applications due to its mechanical strength, availability, and cost-effectiveness, but it is highly susceptible to corrosion in acidic environments [3], [5]. Analytical grade hydrochloric acid was used to prepare a 2 M corrosive medium.

The authors appreciate this important observation. The choice of 2 M HCl was based on its widespread use as a standard aggressive acidic medium in corrosion studies of mild steel, particularly in industrial processes such as acid pickling, descaling, oil-well acidizing, and cleaning operations. At this concentration, hydrochloric acid provides sufficiently accelerated corrosion conditions to effectively evaluate inhibitor performance within a practical experimental timeframe. Furthermore, several published studies on plant-based corrosion inhibitors have employed similar HCl

concentrations, enabling meaningful comparison of inhibition efficiencies and adsorption behavior with literature reports [8].

A 2 M HCl solution was selected because it simulates highly aggressive acidic conditions commonly encountered during industrial acid cleaning, pickling, and oil-well acidizing operations involving mild steel equipment.

Fresh leaves of *Cassia occidentalis*, *Lantana camara*, and *Ricinus communis* were selected for inhibitor extraction based on their availability, non-edible nature, and reported corrosion inhibition potential of plant-based materials [4], [5].

2.2 Preparation of Plant Extracts

The plant leaves were thoroughly washed with distilled water to remove surface impurities, air-dried, and ground into fine powder. The powdered samples were subjected to solvent extraction using standard procedures commonly employed for obtaining plant-based corrosion inhibitors [4], [6]. The resulting extracts were filtered and concentrated, and the prepared extracts were used directly for corrosion inhibition studies.

The plant powders were extracted using ethanol–water solvent systems under reflux conditions to ensure efficient recovery of phytochemical constituents responsible for corrosion inhibition. Fifty grams (50 g) of each powdered plant sample were refluxed in 500 mL of 70% ethanol–30% distilled water solvent mixture for 4 h at 65 °C. The resulting mixtures were filtered using Whatman No. 1 filter paper and concentrated under reduced pressure using a rotary evaporator at 40 °C to obtain crude extracts

2.3 Preparation of Mild Steel Specimens

Mild steel coupons of known dimensions were mechanically polished using successive grades of abrasive paper to obtain a smooth surface. The specimens were degreased with ethanol, rinsed with distilled water, and dried before immersion. Proper surface preparation is essential to ensure reproducible corrosion measurements and reliable inhibitor performance evaluation [3], [10].

2.4 Phytochemical Analysis

Qualitative phytochemical analysis of the plant extracts was carried out using standard screening methods to identify major bioactive constituents that may contribute to corrosion inhibition. The extracts were tested for alkaloids, tannins, flavonoids, saponins, carbohydrates, anthraquinones, and cardiac glycosides based on characteristic color changes or precipitate formation following the addition of specific reagents. Such phytochemical constituents have been widely reported to influence adsorption behavior and corrosion inhibition efficiency [4], [10]. The results of the phytochemical screening are presented in Table 1

Table 1. Phytochemical constituents of the plant extracts

Phytochemical constituent	<i>Lantana camara</i> leaves	<i>Ricinus communis</i> leaves	<i>Cassia occidentalis</i> leaves
Alkaloids	++	+++	+++
Saponins	++	+	+++
Tannins	+++	++	+++
Flavonoids	+++	++	+++
Carbohydrates	++	++	+
Anthraquinones	+	+	++
Cardiac glycosides	++	+++	+++

Key:

+ = Present

++ = Moderately present

+++ = Highly present

The superior inhibition efficiency of *Cassia occidentalis* is likely associated with phytochemicals such as anthraquinones, flavonoids (quercetin and kaempferol derivatives), tannins, and alkaloids previously reported in the plant. These compounds possess multiple hydroxyl groups, aromatic π -electron systems, and heteroatoms capable of donating electrons to the mild steel surface, thereby promoting strong adsorption and protective film formation.

2.5 Elemental Analysis of Mild Steel

Elemental composition was determined using Energy Dispersive X-ray Spectroscopy (EDX) coupled with scanning electron microscopy (SEM)

Elemental analysis of the mild steel specimen was carried out to determine its chemical composition before corrosion testing. This analysis was performed to confirm the suitability of the material as mild steel and to establish a baseline understanding of its elemental constituents, which may influence corrosion behavior [3]. The elemental composition was expressed in terms of atomic and weight percentages, and the results are presented in Table 2.

Table 2. Elemental composition of the mild steel specimen

Atomic number	Symbol	Element	Atomic concentration (%)	Weight concentration (%)
26	Fe	Iron	53.41	77.44
6	C	Carbon	22.95	7.16
8	O	Oxygen	6.20	2.58
14	Si	Silicon	3.09	2.25
5	B	Boron	6.21	1.74
13	Al	Aluminum	2.05	1.43
47	Ag	Silver	0.51	1.41
41	Nb	Niobium	0.52	1.26
19	K	Potassium	0.76	0.77
30	Zn	Zinc	0.43	0.74
20	Ca	Calcium	0.65	0.68
16	S	Sulfur	0.77	0.64
15	P	Phosphorus	0.65	0.52
25	Mn	Manganese	0.34	0.48
11	Na	Sodium	0.80	0.48
12	Mg	Magnesium	0.31	0.20
22	Ti	Titanium	0.09	0.12
7	N	Nitrogen	0.26	0.10

Note: Elemental composition was determined using standard elemental analysis techniques.

2.6 Gravimetric (Weight Loss) Method

Gravimetric weight loss measurements were employed to evaluate the corrosion behavior of mild steel in 2 M hydrochloric acid in the absence and presence of plant extracts. The gravimetric method is a widely accepted and reliable technique for assessing corrosion rates and inhibitor performance over extended exposure periods [10], [14]. Pre-weighed mild steel specimens were immersed in the corrosive medium for different exposure times, after which they were retrieved, cleaned, dried, and reweighed to determine weight loss.

The immersion period was extended to 336 h (14 days) to evaluate the long-term stability and persistence of the adsorbed inhibitor films on the mild steel surface. Short-duration studies may only capture initial adsorption behavior, whereas prolonged exposure better reflects realistic industrial conditions where pipelines operate continuously over extended periods. The extended immersion also enabled monitoring of desorption effects and inhibitor durability over time. The exposure duration was extended to 336 h to assess the long-term stability, persistence, and durability of the protective inhibitor films under prolonged acidic exposure.

2.7 Determination of Corrosion Rate and Inhibition Efficiency

The corrosion rate of mild steel was calculated from the measured weight-loss values using standard corrosion evaluation expressions. At the same time, the inhibition efficiency was determined by comparing the corrosion rates obtained in the absence and presence of the plant extracts [3], [10]. These parameters were used to assess the effectiveness of the plant extracts as corrosion inhibitors and to evaluate their performance with increasing exposure time.

The corrosion rate of mild steel was calculated from weight loss measurements using the standard expression:

$$CR = \frac{W}{A \times t} \quad (1)$$

Where:

CR = corrosion rate

W = weight loss

A = coupon surface area

t = immersion time

2.8 Adsorption Consideration

The adsorption behavior of the plant extracts on the mild steel surface was assessed qualitatively based on inhibition efficiency trends and surface coverage considerations. Variations in corrosion rate and inhibition efficiency with exposure time were used to infer the nature of the interaction between inhibitor molecules and the metal surface. This qualitative approach has been widely adopted in gravimetric corrosion inhibition studies involving plant-derived inhibitors [10], [14].

3. RESULTS AND DISCUSSION

3.1 Effect of Plant Extracts on Weight Loss

The effect of plant extracts on the weight loss of mild steel in 2 M hydrochloric acid was evaluated using the gravimetric method at different exposure times. Gravimetric

weight loss measurement is a widely used technique for assessing corrosion behavior and inhibitor performance under prolonged exposure conditions [10], [14]. The weight loss values obtained for the uninhibited and inhibited systems are presented in Table 3.

Table 3. Corrosion rate of mild steel in 2 M hydrochloric acid at room temperature (Blank)

Exposure time (h)	Weight loss (g)	Corrosion rate ($\times 10^{-6}$ cm/day)
24	0.685	9590.94
48	1.261	8827.86
72	1.798	8391.49
96	2.316	8106.79
120	2.775	7770.76
144	3.225	7525.74
168	3.625	7250.71
192	4.011	7179.84
216	4.396	6838.89
240	4.762	6667.45
264	5.234	6662.11
288	5.497	6413.79
312	5.744	6186.45
336	6.246	6246.61

Note: Corrosion rate values were calculated from weight loss measurements using Equation (1).

The results show that mild steel experienced significant weight loss in the uninhibited acidic medium, confirming the aggressive nature of the 2 M hydrochloric acid solution. In contrast, the presence of plant extracts substantially reduced the weight loss of mild steel at all exposure times, indicating effective corrosion inhibition. The reduction in weight loss suggests that inhibitor molecules adsorbed onto the metal surface, thereby limiting direct contact between the mild steel and the corrosive medium. Similar reductions in weight loss in the presence of plant-based inhibitors have been widely reported in the literature [6]–[9], [10]

3.2 Corrosion Rate and Inhibition Efficiency

The corrosion rate and inhibition efficiency of mild steel in 2 M hydrochloric acid were calculated from the gravimetric weight loss data for both the blank solution and the inhibited systems at different exposure times, following established corrosion evaluation procedures [3], [10]. The results obtained in the presence of *Lantana camara*, *Cassia occidentalis*, and *Ricinus communis* extracts are presented in Tables 4–6

Table 4. Corrosion rate and inhibition efficiency of mild steel in 2 M hydrochloric acid containing *Lantana camara* leaf extract

Exposure time (h)	Weight loss (g)	Corrosion rate ($\times 10^{-6}$ cm/day)	Inhibition efficiency (%)
24	0.030	420.04	95.62
48	0.083	581.06	93.42
72	0.096	448.04	94.66
96	0.144	504.05	93.78
120	0.148	414.44	94.67
144	0.205	478.38	93.64
168	0.210	420.04	94.21
192	0.244	427.04	94.05
216	0.314	488.49	92.86
240	0.371	519.45	92.21

Exposure time (h)	Weight loss (g)	Corrosion rate ($\times 10^{-6}$ cm/day)	Inhibition efficiency (%)
264	0.407	518.05	92.22
288	0.432	504.05	92.14
312	0.444	478.20	92.27
336	0.499	499.05	92.01

Note: Corrosion rate values were calculated from weight loss data using Equation (1). The inhibitor volume was maintained constant throughout the experiment.

Table 5. Corrosion rate and inhibition efficiency of mild steel in 2 M hydrochloric acid containing *Cassia occidentalis* leaf extract

Exposure time (h)	Weight loss (g)	Corrosion rate ($\times 10^{-6}$ cm/day)	Inhibition efficiency (%)
24	0.049	686.07	92.85
48	0.063	441.04	95.00
72	0.105	490.05	94.16
96	0.111	388.54	95.21
120	0.157	439.64	94.34
144	0.192	448.04	94.05
168	0.200	400.04	94.48
192	0.211	369.29	94.86
216	0.220	342.23	95.00
240	0.226	316.43	95.25
264	0.323	411.13	93.83
288	0.343	400.21	93.76
312	0.353	380.19	93.85
336	0.370	370.04	94.08

Note: Corrosion rate values were calculated from weight loss data using Equation (1). The inhibitor volume was maintained constant throughout the experiments.

Table 6. Corrosion rate and inhibition efficiency of mild steel in 2 M hydrochloric acid containing *Ricinus communis* leaf extract

Exposure time (h)	Weight loss (g)	Corrosion rate ($\times 10^{-6}$ cm/day)	Inhibition efficiency (%)
24	0.092	1288.13	86.57
48	0.155	1085.11	87.71
72	0.189	882.09	89.49
96	0.258	903.09	88.86
120	0.297	831.68	89.30
144	0.330	770.08	89.77
168	0.359	718.07	90.10
192	0.434	759.57	89.42
216	0.474	737.41	89.22
240	0.485	679.07	89.82
264	0.586	745.89	88.80
288	0.632	737.41	88.50
312	0.643	692.53	88.81
336	0.714	714.07	88.57

Note: Corrosion rate values were calculated from weight loss data using Equation (1). The inhibitor volume was maintained constant throughout the experiment.

The corrosion rate values showed that mild steel corroded rapidly in the absence of inhibitors, while the introduction of plant extracts significantly reduced corrosion rates throughout the exposure period. The calculated inhibition efficiency values indicate that the plant extracts provided substantial corrosion protection over time, with relatively stable efficiencies observed despite prolonged exposure. These

results demonstrate the ability of the plant extracts to maintain effective surface coverage, thereby suppressing metal dissolution. Comparable trends in corrosion rate reduction and inhibition efficiency have been reported for other plant-derived inhibitors in acidic environments [6]–[9], [10].

The slight fluctuations in corrosion rate observed for *Lantana camara* during the early immersion period may be attributed to temporary adsorption–desorption equilibria and restructuring of the protective phytochemical layer on the metal surface.

3.3 Comparative Performance of Plant Extracts

A comparative evaluation of the corrosion rate and inhibition efficiency of mild steel in the absence and presence of the different plant extracts was carried out to assess their relative inhibition performance. The comparative corrosion behavior of the uninhibited and inhibited systems is summarized in Table 7.

Table 7. Comparative corrosion rate of mild steel in 2 M hydrochloric acid with and without plant extracts

Exposure time (h)	Blank solution (cm day ⁻¹)	<i>Lantana camara</i> (cm day ⁻¹)	<i>Cassia occidentalis</i> (cm day ⁻¹)	<i>Ricinus communis</i> (cm day ⁻¹)
24	0.009591	0.000420	0.000686	0.001288
48	0.008828	0.000581	0.000441	0.001085
72	0.008391	0.000448	0.000490	0.000882
96	0.008107	0.000504	0.000389	0.000903
120	0.007771	0.000414	0.000440	0.000832
144	0.007526	0.000478	0.000448	0.000770
168	0.007251	0.000420	0.000400	0.000718
192	0.007180	0.000427	0.000369	0.000760
216	0.006839	0.000488	0.000342	0.000737
240	0.006667	0.000519	0.000316	0.000679
264	0.006662	0.000518	0.000411	0.000746
288	0.006414	0.000504	0.000400	0.000737
312	0.006186	0.000478	0.000380	0.000693
336	0.006247	0.000499	0.000370	0.000714

Note: Corrosion rate values were calculated from weight loss measurements using Equation (1).

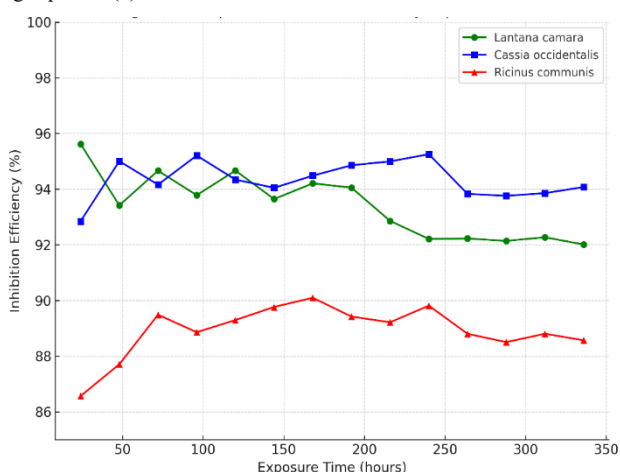


Fig. 1. Comparative inhibition efficiency of mild steel in 2 M hydrochloric acid in the presence of *Cassia occidentalis*, *Lantana camara*, and *Ricinus communis* leaf extracts.

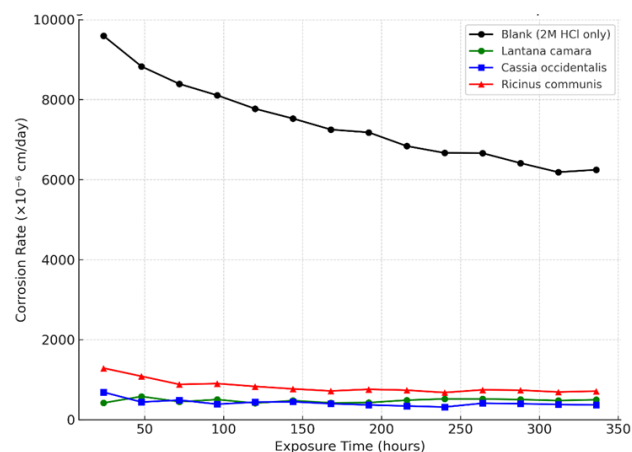


Fig. 2. Comparative Corrosion rate of mild steel in 2 M HCl with and without plant extracts (*Lantana camara*, *Cassia occidentalis*, and *Ricinus communis*)

Comparative analysis revealed that *Cassia occidentalis* exhibited the highest inhibition efficiency and lowest corrosion rate among the investigated extracts, followed by *Lantana camara*, while *Ricinus communis* showed comparatively lower, though still significant, inhibition performance. The observed differences in inhibition efficiency can be attributed to variations in the chemical composition and adsorption capability of the plant extracts. Similar comparative behavior among different plant-based inhibitors has been documented in previous studies [4], [6]–[9], [10].

3.4 Mechanism of Corrosion

The corrosion inhibition behavior of the plant extracts was further examined to elucidate the underlying inhibition mechanism based on experimental observations and phytochemical composition of the extracts.

The corrosion inhibition performance of the plant extracts observed in this study can be attributed to the adsorption of phytochemical constituents onto the mild steel surface. Qualitative phytochemical analysis confirmed the presence of adsorption-active compounds such as alkaloids, flavonoids, tannins, and saponins in the plant extracts (Table 1). These compounds contain heteroatoms and π -electron systems that facilitate interaction with metal surfaces and promote the formation of a protective adsorbed layer. The sustained inhibition efficiency observed over increasing exposure time suggests that the adsorbed inhibitor layer remained effective throughout the duration of the experiment. Adsorption-based inhibition mechanisms have been widely reported for plant-derived corrosion inhibitors in acidic environments [4], [10], [12], [14].

The selected plants are non-edible, locally abundant, and widely regarded as invasive or underutilized species in many tropical regions. Their utilization as corrosion inhibitors therefore minimizes competition with food resources while promoting biomass valorization. For industrial-scale application, cultivation and controlled harvesting strategies would be necessary to ensure sustainable supply chains and ecological balance.

Because these plants are non-edible and widely available, their utilization supports sustainable biomass valorization while avoiding competition with food resources.

4. CONCLUSION

This study demonstrated the effectiveness of non-edible plant extracts as corrosion inhibitors for mild steel in a 2 M hydrochloric acid medium. Gravimetric weight loss measurements showed that the presence of the plant extracts significantly reduced the corrosion rate of mild steel compared to the uninhibited system across all exposure periods. The inhibition efficiency was observed to remain effective with increasing exposure time, indicating sustained corrosion protection.

Comparative evaluation of the extracts revealed that *Cassia occidentalis* exhibited the highest inhibition efficiency, followed by *Lantana camara* and *Ricinus communis*. The differences in inhibition performance among the extracts were attributed to variations in their phytochemical composition, as qualitative analysis confirmed the presence of adsorption-active constituents such as alkaloids, flavonoids, tannins, and saponins.

The corrosion inhibition behavior observed in this study supports an adsorption-controlled mechanism, in which phytochemical constituents adsorb onto the mild steel surface over time to form a protective layer that restricts metal dissolution in the acidic environment. These findings highlight the potential of non-edible plant extracts as effective, low-cost, and environmentally sustainable alternatives to conventional synthetic corrosion inhibitors for corrosion control in acidic industrial applications.

Elevated temperatures generally reduce inhibition efficiency by weakening physically adsorbed protective films and increasing desorption of phytochemicals from the metal surface. Higher temperatures also accelerate diffusion and metal dissolution kinetics, thereby increasing corrosion rates. The observed decrease in inhibition efficiency with increasing temperature therefore supports a predominantly physisorption-controlled mechanism.

The authors acknowledge that the present work was conducted under static immersion conditions, which may differ from dynamic industrial pipeline environments. Under flowing conditions, shear stress and turbulence could weaken physically adsorbed inhibitor films and reduce inhibition efficiency. However, the consistently high efficiencies observed over 336 h suggest reasonably stable adsorption behavior. Future work will include flow-loop and electrochemical impedance studies to evaluate inhibitor stability under hydrodynamic conditions representative of industrial pipelines.

A preliminary economic consideration indicates that the investigated plant extracts may offer lower production costs than conventional synthetic inhibitors because the plants are locally abundant, non-edible, and require minimal processing. While commercial synthetic inhibitors may cost approximately USD 5–20 per kilogram depending on formulation, crude plant extracts prepared from locally sourced biomass may be produced at substantially lower cost, particularly in regions where the plants are considered invasive or agricultural waste. A detailed techno-economic analysis is recommended for future large-scale implementation studies.

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